The Atmospheres of Directly Imaged Planets: Where has all the Methane Gone?

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Methane and ammonia both first appear at lower effective temperatures in brown dwarf atmospheres than equilibrium chemistry models would suggest. This has traditionally been understood as a consequence of vertical mixing timescales being shorter than chemical equilibration timescales in brown dwarf photospheres. Indeed the eddy diffusivity, a variable accounting for the vigor of vertical mixing, has become a standard part of the description of brown dwarf atmosphere models, along with $T_{\rm eff}$ and log g. While some models have suggested that methane is less favored at lower gravity, the almost complete absence of methane in the atmospheres of directly imaged planets, such as those orbiting HR 8799, even at effective temperatures where methane is readily apparent in brown dwarf spectra, has been puzzling. To better understand the paucity of methane in low gravity atmospheres we have revisited the problem of methane chemistry and mixing. We employed a 1-D atmospheric chemistry code augmented with an updated and complete network of the chemical reactions that link CO to CH_4. We find the methane abundance at altitudes at or above the effective photosphere is a strong function of surface gravity because higher g shifts the p-T structure to higher pressures (i.e., a given optical depth is proportional to p/g, a relation mitigated somewhat by pressure broadening). Thus quenching in more massive brown dwarfs occurs at a lower temperature and higher pressure, both favoring CH_4. We predict that in the lowest mass young giant planets, methane will appear very late, at effective temperatures as low as 600 K rather than the 1200 K seen among field brown dwarfs. This methane deficiency has important implications for the interpretation of spectra as well as methane-based planetary companion searches, such as the NICI survey. The GPI and SPHERE surveys will test these ideas and probe atmospheric chemistry and composition in an entire new range of parameter space. A caveat is that these calculations presume that the C to O ratio is comfortably less than one; the behavior is quite different if C and O are equally abundant, and of course CH_4 is always present if C exceeds O.